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1 Carbonate cementing minerals in rhizoliths from Badain

2 Jaran Desert: implication for pedo-diagenesis and

3 environment of dune soil

4
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20 21 **Abstract**

22 Pedogenic carbonates are a good proxy of soil formation and functioning because
23 the morphology of minerals is directly related with the processes of
24 dissolution–precipitation. Carbonate rhizolith is one type of pedogenetic carbonate
25 forming in modern soils of dunes and loess. The calcite micro-morphology with the
26 sedimentary hydrogeochemical conditions prevailing during their formation remains
27 open. Electron microscopy with an X-ray energy dispersive spectrometer and X-ray
28 diffraction were used to investigate in detail the micro-morphology of carbonate
29 cements of the rhizoliths and obtain paleoenvironmental information in the dune soil
30 of Badain Jaran Desert in Northwest China. Two types of carbonates rhizoliths,
31 primary rhizoliths (PR) and reworked rhizoliths (RR), were found. The PRs are

32 present *in situ* within dune soils. The RRs are being eroded out from soil, potentially
33 dislocated or transferred, and weathered at the soil surface. PRs displayed
34 homogeneous micritic mass of calcite crystals, with pores, cavities and voids among
35 the mass. RRs displayed various morphologies of calcite crystals (polyhedral,
36 euhedral rhombic, tooth-like, prismatic and pillar), rosettes, short rods, and calcified
37 fungal hyphae. The diagenesis differences at soil depth and surface affected the
38 crystal morphologies. The homogeneous micritic mass of calcite crystals of the PRs
39 were formed during the early diagenesis, preferentially in wet soils with semi-closed
40 and semi-redox conditions. In contrast, the cementing minerals of the RRs became
41 bigger and clearer in the late diagenesis than during early diagenesis due to
42 recrystallization in open, dry and oxidative conditions at the soil surface. Therefore,
43 the cement crystal morphologies of the rhizoliths can reflect the local environmental
44 and climatic conditions. These objects can be used as environmental and
45 pedo-diagenesis proxies in dune soil or sediments, recording the associated conditions
46 of moisture, temperature, wind, erosion, weathering, solar radiation at the soil surface
47 or at depth. Therefore, assessing the micromorphology of pedogenic carbonates has
48 important implications for soil ecology and evolution as well as plant root physiology
49 in deserts.

50

51 **Keywords**

52 Carbonate minerals; Scanning electron microscopy; Energy dispersive X-ray
53 spectroscopy; X-ray diffraction; Crystal morphology; Soil diagenesis environment

54

55 **1.Introduction**

56 Calcium carbonate (CaCO_3) mostly exists in three crystalline forms, which are,
57 in the order of stability, calcite, aragonite and vaterite (e.g., [Gopi et al., 2013](#); [Sekkal
58 & Zaoui, 2013](#); [Addadi & Weine.,1997](#); [Simkiss, 1964](#)). Vaterite crystals have a
59 hexagonal structure, and aragonite crystals show an orthorhombic structure, while

60 calcite crystals present a rhombohedral structure (Liendo et al., 2022; Jimoh et al.,
61 2018). Investigating the micro-morphology of calcium carbonate in soils, sediments
62 and rocks can help in reconstructing past environmental conditions (Alonso-Zarza,
63 2018; Verrecchia & Verrecchia, 1994; Monger et al., 1991) The occurrence and
64 morphology of pedogenic carbonates, including size, shape and distribution are
65 valuable indices of pedo-environments and pedogenic processes (Golubtsov et al.,
66 2021; Nyachoti et al., 2017; Durand et al., 2018; Diaz-Hernandez et al., 2018; Milliere
67 et al., 2018; Eren et al., 2018).

68 Calcium carbonate found specially in rhizosphere microecosystems shows a
69 unique relationship with several factors such as organic matter, micro-organism and
70 plant distribution, as well as moisture and leaching processes (Huguet et al., 2020;
71 Casado et al., 2014; Becze-Deák et al., 1997). Carbonate micro-morphology includes
72 calcified root cells (*Microcodium*), CaCO₃ hypocoatings, needle fiber calcite,
73 powdery calcite coatings, and calcite pseudomorphs on gypsum (Golubtsov et al.,
74 2021; Kosir, 2004; Becze-Deák et al., 1997). However, despite many decades of
75 thorough descriptive and interpretative work of these minerals, relating calcite
76 micro-morphology with the predominant sedimentary hydrogeochemical conditions
77 during their formation remains a challenge. Environmental interpretations of the
78 calcite micro-morphology have been hampered by the fact that the calcite
79 morphogenesis results from complex interactions between different physico-chemical
80 parameters which often act simultaneously (e.g., carbonate mineral supersaturation,
81 Mg/Ca ratio of the parental fluid, organic and inorganic additives, Mercedes-Martín et
82 al., 2021).

83 The micro-morphology of calcium carbonate within carbonate rhizoliths, such as
84 calcite rhomb chains, isolated calcite rhombs, calcified spherical bodies, calcified
85 epilithic and chasmolithic filaments, grain-coating calcite needle mats, is related to
86 their formation characteristics (Jones & Ng, 1988). Since the factors controlling the
87 morphology of calcite crystals are not fully understood, it is necessary to rely on other
88 materials to obtain an insight into this aspect of the problem. There is probably no

89 universal cementation scheme for rhizoliths, the characteristics of the cements being a
90 function of the local conditions. The nature of the plants themselves may play an
91 extremely important role in the cementation of rhizosphere (Sun et al., 2021, 2020;
92 Marasco et al., 2018) or within roots (Huguet et al., 2021; Luo et al., 2021; Gocke et
93 al., 2014). Plants were shown to have an obvious effect on the diagenesis of
94 carbonates in vadose environments (Sun et al., 2021, 2020; Marasco et al., 2018;
95 Jones & Ng, 1988). Nevertheless, the characteristics of the cements can be controlled
96 to a large extent by the activity of the microorganisms that are associated with the
97 plant roots.

98 A large number of studies on rhizoliths has been published over the last decades,
99 but detailed investigations of the microscopic morphology of calcium carbonate
100 within carbonate rhizoliths remain scarce, with the description of microscopic
101 morphology of calcium carbonate included in some case studies (e. g., Sun et al., 2021,
102 2020, 2019a, b,c; Gao et al., 2020a, b; Huguet et al., 2020; Li et al., 2020, 2017,
103 2015a, b; Zhu et al., 2019; Alonso-Zarza, 2018; Barta, 2011; Klappa, 1980).
104 Nevertheless, pedogenic carbonates are a good promising proxy of soil formation and
105 functioning because the morphology of minerals is directly related with the processes
106 of dissolution–precipitation. Thus, they can provide information on climate and water
107 regime dynamics during or even after the lifetime of plants, whose roots entail
108 formation of these structures. Electron microscopy with an X-ray energy dispersive
109 spectrometer (SEM/EDS) was shown to be a powerful tool to investigate in detail the
110 micro-morphology of carbonate cements and obtain paleoenvironmental information
111 (Kuznetsova & Khokhlova, 2012).

112 Apart from many other known areas worldwide, carbonate rhizoliths of the
113 Alashan Deserts of Northwest China have been intensively studied over the recent
114 years using different tools (lipid biomarkers, ¹⁴C dating, major and trace elements,
115 phytoliths, cementing mineral morphology, carbon and oxygen isotopes), allowing the
116 historical analysis of climate change (Sun et al., 2021, 2020, 2019a, b; Li et al., 2020,
117 2017, 2015a, b; Gao et al., 2020a, b; Zhu et al., 2019). However, only few information

118 on rhizolith genesis were obtained. Several key issues remain open, such as the age
119 and formation mechanisms of the rhizoliths, including the influence of the vegetation
120 type and soil microbial diversity on the formation of these objects (Sun et al., 2021,
121 2020). For instance, the rhizolith ages remain often unclear due to the age
122 discrepancies between their carbonate cementing minerals and the inner root relicts
123 (Sun et al., 2019a). The influence of climate change on the root tubes (Li et al., 2015)
124 has still to be investigated. This is even further complicated by the fact that the
125 rhizoliths are often not found in intact relationship with their forming plants. The
126 identification of traces of life based on rhizolith characterization is usually
127 challenging, especially in very old rocks, as the morphological and chemical
128 signatures of biominerals and microfossils are subtle, of microscopic size and
129 inevitably altered with aging. Nevertheless, the rhizoliths of the Alashan Deserts are
130 of special interest, as they were shown to form only around the dead roots of
131 *Artemisia* and to save the complete information of mineralization of calcium
132 carbonate during Holocene in modern dune soils through pedodiagenetic effects (Sun
133 et al., 2021, 2020). Therefore, this work aimed at investigating the micro-morphology
134 of calcium carbonate of the rhizoliths occurring in dune soils from Badain Jaran
135 Desert in the Alashan Deserts. Such a study was performed using SEM, EDX and
136 XRD. The cement micro-characteristics of the carbonate rhizolith were related to the
137 environmental conditions and processes taking place in and on the soils, allowing to
138 better constrain the conditions of these objects as environmental proxies. This study
139 provides a reference and model for future rhizolith studies of deserts worldwide.

140

141 2. Study area

142 Badain Jaran Desert (BJD) (39°04'15"N to 42°12'23"N, 99°23'18"E to
143 104°34'02"E) is in North-western China (Fig. 1a, b), covering an area of
144 approximately 52,100 km². It is subjected to a transitional climate between the Asian
145 summer monsoon and westerly belt (Wang F., et al., 2015). The elevations of the BJD

146 range between 1,000 and 1,500 m a.s.l. and decrease from southeast to northwest (Zhu
147 et al., 2010). This desert comprises the tallest mega-dunes the world, generally
148 200–300 m high and 3-5 km long, with lakes frequently occurring between the dunes.
149 The latter are especially dense in the south-eastern portion, where they can reach up to
150 500 m a.s.l. Towards the northwest alluvial/lacustrine plain, the size of sand dunes
151 progressively decreases and the lakes gradually disappear (Fig. 1, 2).

152 The mean annual precipitation is currently 40–120 mm, falling mainly in
153 summer. The mean annual potential evaporation is over 2500 mm. The conventional
154 precipitation (below 5 mm) accounts for approximately 90% of rainfall events (Wang
155 et al., 2013). The soil heat flux shows the largest diurnal variations at 5 cm depth and
156 only slight variation at 20 cm depth (Li et al., 2012). The mean annual air temperature
157 ranges from 9.8 to 10.2°C and the mean annual wind speed varies from 2.8 to 4.6 m/s.
158 The prevailing wind direction over the year is northwest, related to the winter
159 monsoon from the Siberian High-Pressure System (Zhang et al., 2017).

160 The vegetation of this desert is dominated by shrubs and subshrubs, including
161 *Artemisia*, *Agriophyllum*, *Triglochin*, *Glaux*, *Aeluropus*, *Haloxylon*, *Nitraria*, *Tamarix*,
162 and *Reaumuria* species (Wang M. et al., 2015; Yang et al., 2003).

163 The dune soil sand sources are the weathered debris and sediments of the
164 northwest Gobi and the alluvial fan of the Heihe river. The northwest winds and
165 windstorms have transported them to the desert (Fig. 1. Dong et al., 2013, 2009). The
166 grain size of surface sand is dominated by well-sorted, rounded, pinky-grey, middle to
167 fine sand (of feldspar and quartz), containing only slight amount of melanocratic
168 minerals (such as hornblende, pyroxene and magnetite). Carbonate minerals are in
169 low abundance in the silicate desert sands (Bai, 2011; Gates et al., 2008). The average
170 carbonate content in soils was reported as 4.6 % by Wang et al. (2004) and 6.5 % by
171 Sun et al. (2019a).

172 The thickness of the upper dry layer of the mega-dunes in this desert is only
173 about 20-30 cm, with a conspicuous wet layer under the upper dry layer. Between
174 0.2-1.5 m depth, the water content is usually 1-5% (wt, Wang et al., 2019; Zhao et al.,

175 2011; Gu et al., 2004) and is up to 10% at 90 cm depth with well-preserved sand
176 bedding (Liu et al., 2016). At 2 m depth, water content is about 65% (pore saturation;
177 Zhao et al., 2011). Water in the sandy soil layer is mainly divided into adsorbed water
178 and gravity water. Adsorbed water exists in the form of a water film and is thus
179 termed film water. It is generally thought that if the water content of the sand layer is
180 <3% then it is adsorbed water, and if the water content is >3% then it is gravity water.
181 Adsorbed water, which is derived from rainfall, moves slowly downwards and is
182 generally a minor contribution to groundwater (Zhao et al., 2017). In contrast, gravity
183 water moves rapidly downwards within a soil and is the most important supplement of
184 groundwater in depressions and lakes. Gravity water with a content above 5% (wt)
185 was found in some sand layers of the BJD (Zhao et al., 2017). The precipitation in this
186 desert plays an important role by providing water to the soils and lakes (Ma et al.,
187 2019; Yue et al., 2019). However, in somewhere in the hinterland of the desert, the
188 soil water contents are uneven and variable from 0.36-2.98% along depth changes
189 from 4.3-9.7m, due to micro-geomorphologies differences (Dong et al., 2022; Zhao et
190 al., 2017). Soil water content is less in the surface soil because it suffers stronger
191 evaporation, while the deep soil water (> 200 cm) is hardly influenced by the
192 evaporation (Jin et al., 2021).

193

194 3. Methods

195 Because of the vast sand sea area, poor accessibility and the dominance of an
196 extremely arid climate, field explorations were only conducted in zones located in the
197 south-eastern part of the desert, where many mega-dunes, lakes and low small dunes
198 next to the desert margin are present (Fig. 1, 2). In the exploration area in the
199 hinterland of the desert, rhizoliths were only found at six sites (Fig. 2, red points A-F).
200 Detailed survey and examinations for landscape, vegetation, modern root,
201 sediment/soil, rhizolith exposure and morphology were carried out around these sites.
202 At each site the most representative samples of carbonate rhizoliths and their typical

203 features were intensively described and photographed. Typical rhizolith samples were
204 collected for laboratory analyses and further photographing (Sun et al., 2021).

205 Care was taken to keep the rhizoliths intact for detailed description of their
206 characteristics in the field down to the ultramicroscopic observations in the laboratory.
207 Samples were chosen based on their typical external characteristics for determining
208 scanning electronic microscopy. Energy dispersive X-ray spectroscopy,
209 micro-morphological texture and cement mineralogy analyses by microscopy, as well
210 as cathodoluminescence and staining were all performed at the Institute of Northwest
211 Petroleum Geology, Lanzhou, China (Sun et al., 2021). The micro-scale morphology
212 and chemical compositions of the rhizolith cement were determined by scanning
213 electronic microscopy (SEM; FEI Quanta 450) coupled with Energy dispersive X-ray
214 spectroscopy (EDS). Fragments of the rhizoliths were gold coated, and then analysed
215 by SEM coupled with EDX, as previously described (Sun et al., 2021). Powder X-ray
216 diffraction (XRD) was recorded on a Japan Rigaku Smart Lab X-ray diffractometer
217 using Cu-K α irradiation ($\lambda= 0.154056$ nm) to determine the mineral phase, and the
218 sample was scanned from 10 to 70° 2 θ and at a step of 0.02°, at CAS Key Laboratory
219 of Crust-Mantle Materials and Environments, School of Earth and Space Sciences,
220 University of Science and Technology of China, Hefei, China. The
221 micro-morphological terms of carbonate minerals crystals are employed based on
222 Mercedes-Martín et al. (2021) and Minerals.net
223 (<https://www.minerals.net/mineral/calcite.aspx>).

224

225 **4. Results**

226 **4.1. Field features of rhizoliths**

227 Two types of rhizoliths were distinguished based on the outcrop states: reworked
228 (RR) and primary rhizoliths (PR). The RRs are being eroded out from soil, potentially
229 translocated and weathered on the soil surface under solar radiation and wind erosion,
230 and they are thinner and harder than the PRs. In contrast, the PRs are present within

231 dune soils and keep their original characteristics *in situ*, without being eroded,
232 transferred and weathered.

233 **4.1.1 RRs on soil surface**

234 RRs were only found in Sites A, B and C. Their general features are described
235 below.

236 At site A (Sumujilin Lake, 39°48'N, 102°26'E), the rhizolith outcrops were
237 found at the feet of the windward gentle slopes of the mega-dunes situated above the
238 east of the Sumujilin Lake (Fig. 3a). Brown purple RRs were present as fragments
239 eroded out of the sand. The fragments of typical rhizoliths with bright dark brown
240 colour and rills are hard and varnished brightly. Their centres are hollow (Fig. 3b).

241 At Site B (Nuoertu Lake, 39°46'N, 102°27'E), rhizolith outcrops were found
242 along the gentle slopes of the mega-dunes on the east side of the Nuoertu Lake. RRs
243 occurred as enormous fragments as at Site A. However, the fragments were white,
244 corresponding to the inner parts of the central hollows of former roots subjected to
245 weathering. In some rhizoliths, relicts of fine root hairs were observed. Weathered
246 rills were apparent on the outer surfaces of the big tubes. The small broken pieces of
247 rhizoliths were white and fragile due to weathering (Fig. 4).

248 At Site C (Baoritaolegai Lakes, 39°35'N, 102°28'E), rhizoliths were also
249 found along a windward gentle slope between two mega-dunes, south of Baoritaolegai
250 Lakes. RRs were found as broken tubes. Their general features are similar to the
251 above sites (photos were omitted).

252 **4.1.2 Vertical RRs above soil and PR features within soil**

253 Both PR and RR were found at Sites D, E, F. But the RRs are vertical above
254 soil and they are the upper parts of the PR underground.

255 At Site D (6.0 km east to the Gate of the BJD National Geological Park,
256 39°27'N, 102°26'E), RRs fragments are lying intricately at the sand surface. However,
257 only a few of the RRs were found standing vertically above soil. PRs are present
258 underground, below the vertical standing rhizoliths above soil surface. The upper part
259 above ground is thinner and harder than the underground primary part within soil

260 because of weathering and erosion (Fig. 5a). Once broken, they display decayed root
261 relicts within the central hollowness, surrounded by a white hale carbonate cement
262 (Fig. 5b). After having been dug out for some time, they became harder quickly than
263 before due to losing soil water at the site.

264 At Site E (39°25'14.56"N,102°8'55.25"E), their general features are similar to
265 those of Site D. After having been dug out, the PR show brown interior with
266 preserved root relicts when broken (Fig. 6). PR are soft, while RR are hard.

267 At Site F (39°29'57"N,102°12'48"E), their general features are similar to those of
268 Site D. PR were broken easily by gentle hand-force. The centre of the decayed root
269 relicts is brown (photos were omitted).

270 **4.2. SEM features and EDS mineral compositions of rhizolith cement**

271 Ten rhizolith specimens – one or two from each site - were chosen for laboratory
272 analyses, with determination of micro-morphological texture and mineral composition.
273 Their SEM features differ from each other and are detailed below.

274 **4.2.1 RRs on soil surface**

275 **Site A**

276 The cement of the RR is tight and densely compact around the sand particles (Fig.
277 7a). Some of the cementing minerals show polyhedral crystals and many pores occur
278 within the cement (Fig. 7b). They also display bigger euhedral rhombic crystals, or
279 tooth-like crystals around the walls of the pores, against the dense fine crystal cement
280 background (Fig. 7c). Moreover, they present both aragonite rosette morphology (Fig.
281 7d) and equant polyhedral crystals characterized by well-developed crystal faces and
282 slightly smooth edges and corners (Fig. 7e). Generally, all EDS spectra reveal that the
283 cements are calcium carbonate (Fig. 7f).

284 **Site B**

285 The cement of the RR is compactly tight and dense around sand particles (Fig
286 8a). The morphology of the cementing minerals shows polyhedral (Fig. 8b) and short

287 rods crystals (Fig. 8c). Their mineral compositions are calcite with a little of Mg (Fig.
288 8d) based on EDS analysis.

289 **Site C**

290 The cement of the RR is not as tight and densely compacted around sand
291 particles as it was at sites A and B. However, the cement shows short rods shape (Fig.
292 9a) and calcified fungal hyphae-like networks with many pores, cavities and voids
293 (Fig. 9b). The cement is calcium carbonate, as indicated by EDS (spectrum is
294 omitted).

295 **4.2.2 Vertical RRs and PRs**

296 **Site D**

297 The rhizoliths are constituted of two parts, the upper parts-RR at the soil surface
298 and the lower parts-PR within soil. The RR cement shows short rods crystals (photo is
299 omitted). The PR either displays homogeneous micritic mass (Fig. 10a) with a lot of
300 pores, cavities and voids (Fig. 10b), or dense prism/pillar-like calcite crystals (Fig.
301 10c). The cement is mainly constituted of calcium carbonate with only low amounts
302 of Mg (EDS spectrum is omitted).

303 **Site E**

304 At this site only one PR was analysed. The lab tests of upper RRs were done.
305 The cementing minerals are homogeneous micritic mass, which are growing along the
306 surfaces of sand particles (Fig. 11a). The calcite crystals form thinner layers without
307 obvious and clear crystal shapes and not thick enough to fill the pores among the
308 particles (Fig. 11b, c). Based on EDS analysis, the cement composition is calcium
309 carbonate. (Fig. 11d).

310 **Site F**

311 Similar to site D, the cement of the RRs above soil surface is made of short rods
312 crystals (photo is omitted). The PR within soil display homogeneous micritic mass
313 (Fig. 12), with pores, cavities and voids (photo is omitted). The PR cement is mainly

314 constituted of calcium carbonate with low amounts of Mg and NaCl (EDS spectrum is
315 omitted).

316 The micro-morphologies and compositions of the cementing minerals and their
317 diagenesis features are summarised in the Fig. 13. The micro-morphologies show the
318 following key features: (i) the PRs have homogeneous micritic mass, with pores,
319 cavities and voids; (ii) the RRs on or above soil surface have big and clear (polyhedral,
320 euhedral, rhombic, prismatic, rosette) crystal shapes and short rods, with occasional
321 hair-like, or fungi-form crystals; (iii) vertical upper RRs of the PR have only short
322 rods; (iv) the cement minerals compositions is calcium carbonate with a little of Mg.

323 **4.3. XRD mineral compositions of rhizolith cement**

324 XRD results confirmed that the carbonate cements are all calcite (Fig. 14). In
325 addition, sand particles like quartz and plagioclase feldspars (matched well with
326 standard card of anorthite and anorthite, sodium) were also detected. This is consistent
327 with section cathodoluminescence observations (Sun et al., 2021).

328 At sites A, C and F, SEM showed that aragonite is also present by its shape in
329 the cement. However, no diffraction peaks of aragonite were detected in the
330 corresponding XRD results. Therefore, the content of aragonite is likely too low to be
331 detected by XRD (Fig. 14a, c, f).

332

333

334 **5. Discussion**

335 **5.1 General SEM characteristics of the cement of the PRs and** 336 **biogeochemical implications**

337 **5.1.1 Early diagenesis features within soil**

338 Within the underground dune soil, the diagenesis environment of primary
339 rhizoliths is characterized by weak redox conditions (due to semi-closed conditions)
340 with comparatively higher moisture content, and lower stable temperature than those

341 at the soil surface. Therefore, the conditions of the early diagenesis process are
342 comparatively steady in deep soils.

343 Within soil, vascular plants and symbionts increase chemical weathering of the
344 silicates, which results in increasing of Ca^{2+} and HCO_3^- availability and pedogenetic
345 carbonate production (Brasier, 2011). There are two Ca^{2+} sources for rhizolith cement:
346 1) authigenic carbonates from in situ chemical weathering of soil primary silicate
347 minerals such as feldspar, mica, amphibole and pyroxene; and 2) dissolution of in situ
348 primary lithogenic carbonate rock debris such as limestone and dolomite (Sun et al.,
349 2019a). Moreover, dead root decomposition leads to increased CO_2 and HCO_3^-
350 production around the rhizosphere (Sun et al., 2021,2020). Then dry periods increase
351 the calcium concentration in the soil solution from which CaCO_3 precipitates by the
352 evapotranspiration and release of CO_2 with temperature rise (Sun et al., 2022,
353 2021,2020). Precipitation is also associated with the dissolution and recrystallization
354 of carbonate taking place in the parent matrix, such as soil, sediment and rocks (Eren
355 et al., 2008). In the dune soil of this desert, the semi-closed environment is favourable
356 to both root organic decay and formation of HCO_3^- solutions among the pores of the
357 sandy soil. However, the balance between root decay- CO_2 - HCO_3^- and calcite growth
358 is the key point making the soil micro-environment around the dead roots favourable
359 to the aforementioned process. Such a balance is controlled by factors like soil
360 moisture, soil depth, wind, as well as precipitation or/and temperatures. Such
361 parameters could not be measured in the field but would have been useful to better
362 understand the details of rhizolith diagenesis.

363 5.1.2 Origin and implications of cement crystal micro-morphology

364 Under the aforementioned diagenesis conditions, the cementing minerals of the
365 primary rhizoliths display (i) homogeneous micritic mass in thin layers without
366 obvious and clear crystal shapes, precipitating mainly on particles surface (Fig. 10a;
367 11a, b, c;12); (ii) prism/pillar-like calcite (Fig. 10c); and occasionally (iii) pores,

368 cavities and voids among the micritic mass (Fig. 10b). Their origins and implications
369 are explained as follows.

370 The presence of homogeneous micritic mass implies that the fine calcite crystals
371 were in their initial nucleation and quickly precipitated at the beginning of diagenesis,
372 which cannot be observed even under high magnification (Zhou & Chafetz, 2009;
373 Alonso et al., 2004).

374 The prismatic/pillar-like calcite crystals were subjected to diagenesis for a longer
375 time than homogeneous micritic mass, as shown by the larger size of the former. This
376 suggests that the supersaturation degree of mineral solution changed during the
377 mineralization. During the formation and precipitation of crystals, the solution
378 became supersaturated, allowing the formation of the crystal nucleus. Then, the
379 diffusion and precipitation of ions at the surface of the crystal nucleus led to the
380 crystal nucleus growth and later to the formation of crystal particles and even big
381 crystals when concentrated. If the supersaturation degree is too high, the reaction of
382 Ca^{2+} and CO_2 will be too quick to control the crystal morphology. In contrast, when
383 the supersaturation degree is low, the growth velocity of crystal is low, letting enough
384 time to the formation of the surficial crystal (Cheng et al., 2014). An experiment
385 investigating the precipitation of non-marine calcite confirmed that low calcite
386 supersaturation conditions are prone to form single-crystal prismatic to di-pyramid
387 calcite precipitates (Mercedes-Martin et al., 2021). This suggests that homogeneous
388 micritic mass cement formed rapidly, with enough CO_2 supplied by root decay, and
389 that the short rods calcite crystals formed in low concentration of mineral solutions
390 and/or were subjected to secondary diagenesis after having been formed.

391 The pores, cavities and voids in calcite cement imply that microorganisms and
392 CO_2 gas played key roles in calcium carbonate crystallization through fermentation
393 effect. This is supported by the following evidences from previous studies: (i) These
394 characteristics are similar to those of the carbonate crystals in Mu Us Desert in
395 northern China, with a rough and porous appearance caused by bacterial strains (Liu
396 et al., 2018). Therefore, the pores, cavities and voids in the BJD rhizoliths might be

397 caused by microorganisms. (ii) Irregular carbonate crystals with broken faces and
398 holes on surfaces were suggested to be formed in humid conditions ([Kuznetsova &](#)
399 [Khokhlova, 2012](#)), which could be the case in the BJD. (iii) Increasing contents in
400 (alginic) acid were shown to contribute to the formation of curved and poorly faceted
401 crystal morphology with higher sphericity ([Mercedes-Martin et al., 2021](#)). This means
402 that the pores, cavities and voids of the BJD rhizoliths could have been formed in an
403 acidic microenvironment of soil. The release of CO₂ from *Artemisia* root decay could
404 have led to the formation of such an acidic environment with gas bubbles ([Sun et al.,](#)
405 [2020](#)).

406 These hypotheses are in agreement with the diagenesis features within deep dune
407 soil and with the presence of microorganisms like fungi in the pores among sand
408 particles. In fact, roots and associated microorganisms play a very important role for
409 the pedogenic carbonate formation, not only around living roots ([Eren et al., 2018](#)),
410 but also around dead roots ([Sun et al., 2021,2020](#)). For instance, microbialites have
411 been found in desert soils and tropical forest soils as well. *Myxococcus*, usually found
412 in soils rich in organic matter and decaying material, can precipitate calcium
413 carbonate independently of being metabolically active or killed, though different
414 polymorphs of calcium carbonate can be formed ([Zhu & Maria, 2016](#)). Root decay
415 under microbial decomposition induce gases bubbles in mineral solution and produce
416 calcite with pores, cavities and voids through different metabolic pathways. Most
417 microbial cells provide nucleation sites for carbonate formation, with appearance of
418 microbial textures like cavities, voids, fibric and hair-like shape. Previous studies also
419 confirmed that carbonate precipitation can be caused by soil microorganisms
420 ([Khormali et al., 2020](#); [Menezes et al., 2019](#); [Wang et al., 2016](#); [Zamanian et al., 2016](#);
421 [Vepraskas, 2015](#)).

422 However, there is still an ongoing debate questioning whether the organisms
423 were alive during the calcification ([Eren et al., 2018](#)). Where carbon comes from and
424 whether atmospheric CO₂ can be deposited via this biomineralization process remain
425 unknown, representing an important gap in the knowledge of carbon sequestration via

426 microbial carbonate deposition (Liu et al., 2018). In this case, organisms may use root
427 remains as the source of carbon for biomass growth, resulting in increased
428 concentrations of calcium along the dead roots, with fungi digesting carbon
429 acquisition, leading to CaCO₃ precipitation. This process can take place both at the
430 surface or belowground. It is unclear whether microorganisms act like a catalyst by
431 increasing the medium pH, leading to the saturation of soil solutions and causing
432 calcite precipitation (Barta, 2011). Physicochemical and biogenic processes may have
433 worked together to form variant crystalline forms (Verrecchia & Verrecchia, 1994).
434 Overall, several factors should be further investigated in this desert: (i) the microbial
435 diversity in the bulk soil, both in living and dead rhizosphere; (ii) the microbial
436 influence on calcite formation; (iii) a better understanding of why rhizoliths are
437 formed only around the dead *Artemisia* roots.

438 **5.2 General SEM characteristics of the cement of RRs and** 439 **biogeochemical implications**

440 **5.2.1. Late diagenesis features at soil surface**

441 The Badain Jaren Desert is characterized by large thermal (day-night) amplitude
442 and seasonality, strong wind and little precipitation (cf 2. Study area). The
443 temperature at the desert surface soil can reach up to 70-80°C. Night temperatures in
444 deserts are typically much cooler than daytime temperatures (Khormali & Monger,
445 2020). This heat is transferred into the soil profile downward, with a gradient of about
446 0.5°C per 10 cm until the temperature reaches the approximate mean annual air
447 temperature at a depth of ca. 50 cm (Soil Survey Staff, 1999). Simultaneously, the
448 high-low temperature changes, extreme radiation and strong winds can enhance the
449 aridity of the surface soil, resulting in an increase of the mineral concentration in the
450 soil particle pores. Harsher conditions for microbial growth can be found in shallow
451 desert surface soils vs. deep ones, as only microorganisms resisting to high
452 temperatures can survive (Monger et al., 1991). The RRs are subjected to strong
453 aridity, high temperature changes, solar radiation, and furious wind at the dune

454 surface. Comparatively, the lying RRs on the soil surface are older than the vertical
455 ones which are the upper parts of the PRs above ground.

456 **5.2.2 Origin and implications of cement crystal micro-morphology**

457 The cements of the RRs show the following characteristics: (i) the horizontal
458 lying RRs: polyhedral crystals of calcite with well-developed crystal faces and
459 slightly smooth edges and corners (Fig. 7b, e; 8a, b), or prismatic crystals (Fig. 7c; 8c),
460 rosette shapes (Fig. 7d), calcified fungal hyphae networks (hair-like, or fungi-form
461 crystals (Fig. 9b); (ii) the vertical RRs: short rods of aragonite (Fig. 9a). This implies
462 the following regarding the origin and diagenesis conditions of the RRs:

463 As shown in Fig. 13, homogeneous micritic mass recrystallized to short rods and
464 the short rods recrystallized to big clear (polyhedral, euhedral, rhombic, prismatic,
465 rosette) crystals. Because the vertical RRs were eroded out from PRs present in soil,
466 the formation of these short rods calcite crystals at the dune soil surface was subjected
467 to a different diagenesis from the homogeneous micritic mass of PRs present
468 underground. Recrystallization of homogeneous micritic mass of RRs took place after
469 erosion and weathering due to the loss of soil water and the high temperature near the
470 soil surface. Carbonate accumulations were formed in dry periods and in quiet
471 conditions from solutions of normal concentration (Kuznetsova & Khokhlova, 2012).
472 This is in line with a quick alternation of day-night temperatures (with fog some time)
473 and short shower events in the desert, providing water for dune soil in depth and
474 causing chemical weathering of soil minerals like feldspars and root decaying.
475 Carbonate mineral solution forms in the soil. Then, strong alternating wet and dry
476 conditions (due to strong wind, solar radiation and high temperature) promote and
477 enhance the dissolution and precipitation of CaCO_3 and consequently formation of
478 secondary carbonates (Becze-Deák et al., 1997; Borchardt & Lienkaemper, 1999).
479 The diagenesis conditions at the soil surface support these micromorphological
480 features of calcite cement. It was also confirmed by lab experiments, which showed
481 that higher calcite supersaturation conditions tend to produce polycrystalline calcite

482 grains and corresponding aggregates (Mercedes-Martin et al., 2021). The
483 polycrystalline calcite mentioned above should have been formed in high calcite
484 supersaturation conditions, which were caused by high solar radiation, temperature
485 and aridity around the surface soil.

486 Short rods and rosette shapes means aragonite occurrence in the cement.
487 Aragonite crystals usually show rods (Ma & Feng, 2015; Boyjoo et al., 2014; Cheng
488 et al., 2014; Sarkar & Mahapatra, 2012; Knez et al. 2006). Aragonite is more soluble
489 ($K_{sp}=6.3 * 10^{-9}$) than calcite ($K_{sp}=4.0 * 10^{-9}$) at ordinary pressures and temperatures
490 (25°C), and will commonly precipitate first from solutions. Aragonite is rare compared
491 to calcite because it is thermally unstable and will transform to calcite. This process is
492 more rapid in hydrous environments and at higher temperatures. For example,
493 aragonite generally develops only under hot (e.g., springs) temperature conditions
494 (Zeng et al., 2018; Balthasar & Cusack, 2015; Gutjahr et al, 1996). At ordinary
495 temperatures the transition only takes place by dissolution of aragonite and
496 precipitation of calcite (e.g., Chen et al., 2003; Degens, 1965). Moreover, aragonite is
497 preferentially synthesized over calcite in the presence of (molten lauric) acid as an
498 additive (Sarkar & Mahapatra, 2012). This implies that presence of an organic acid is
499 favourable for aragonite formation. Acid solution formation needs acid gases like CO₂,
500 H₂S, NO₂, etc. from decomposition of organic matter in aqueous soil. The decaying
501 *Artemisia* roots satisfy the acid environment formation in the desert soil (Sun et al.,
502 2021, 2020). The rosette shape particles which were observed result from the
503 aggregation of aragonite rods. These characteristics were supported by the diagenesis
504 features around the shallow soil of this desert. Hence, high temperatures, root
505 decomposition and possible high local Mg/Ca from weathering of soil particles in
506 shallow soil favour aragonite formation.

507 The fact that calcified fungal hyphae networks were found in cement (Fig. 9b) in
508 the shallow soil or above the soil implies that soil microorganisms play a fundamental
509 role in the genesis of calcic soils around the rhizosphere. Biomineralization of calcite
510 by soil microorganisms has important implications for identifying subaerially exposed

511 sediments in the geological column (Wright, 1986). Calcified soil microorganisms, in
512 addition, may serve as useful microfossils that reflect paleoclimatic conditions. The
513 mechanism explaining the production of calcite by microorganisms is probably
514 related to the exudation of excess Ca^{2+} by microorganisms, which concentrate Ca^{2+} on
515 their external surfaces (Phillips et al., 1987). In addition, the production of CO_2 by
516 microbial respiration contributes to the formation of bicarbonate ions (Arnott &
517 Pautard, 1970), which prompts calcite precipitation. Organic matter decomposition is
518 increased by warm temperatures but is decreased by dryness. Overall, such a
519 decomposition is increased when the soil profile receives infrequent precipitation that
520 activates the dormant microbial population. High decomposition rates combined with
521 low carbon inputs explain the low amount of organic carbon in hot deserts (Khormali
522 & Monger, 2020). Calcified hair-like filaments are widely accepted to be of fungal
523 (hyphae) origin, but other micro-organisms such as algae, cyanobacteria,
524 actinomycetes, and eubacteria, and root hairs may also form these filaments (Eren et
525 al., 2018; Durand et al., 2010; Alonso-Zarza et al., 1998). The present results indicate
526 that calcified fungal filaments (Monger et al., 1991) can also be formed in desert soils
527 that were initially noncalcareous, and whose calcite can be attributed to pedogenesis.

528 The relationships between diagenesis environment and micro-morphologies of
529 cementing minerals are summarized in Fig. 13. PRs are in the first step of diagenesis;
530 the vertical upper RRs above ground of the PRs are in the second step of diagenesis;
531 the RRs lying on soil surface are in the last step of diagenesis. The
532 micro-morphologies of cementing minerals of PRs and RRs show different
533 characteristics related to the different diagenesis environments: (i) homogeneous
534 micritic carbonate mass with pores, cavities and voids formed at first diagenesis stage
535 underground; (ii) short rods of aragonite formed at late diagenesis stage with higher
536 temperature; (iii) big and clear carbonate mineral crystals formed at last diagenesis
537 stage. Microorganisms are involved in the formation of calcified fungal hyphae
538 networks in favourable conditions at the dune soil surface, as confirmed by the

539 presence of desert biological soil crust (e.g., [Zhang et al., 2021](#); [Qi et al., 2021](#); [Zhao](#)
540 [et al., 2020](#)).

541

542 **6. Conclusions**

543 The characteristics of the cementing minerals of the carbonate rhizoliths in the
544 Badain Jaran Desert are affected by (micro)environmental conditions in the dune
545 sandy soil. These objects enable the assessment of past environmental conditions that
546 prevailed during their formation.

547 Diagenesis environments are different between the deep and surficial dune soils
548 in the desert. Within the deep soil, the moisture content is higher than at the surface
549 and the temperatures are stable. In contrast, the soil surface is characterized by large
550 day-night temperature amplitude coupled with strong wind deflation, erosion and
551 weathering under solar radiation. Thereafter, primary and reworked rhizoliths are
552 formed within and on the soil, respectively. The primary rhizoliths buried
553 underground, the vertical reworked rhizoliths above soil, and the lying or horizontal
554 root tubes on soil surface correspond to early, middle and late diagenesis steps. The
555 calcium carbonate cement of the PRs buried underground mainly displayed
556 homogeneous micritic mass calcite with pores, cavities and voids. In contrast, the
557 upper vertical parts-RRs of the PRs show short rods-like calcite crystals. However,
558 the lying or horizontal RRs displayed a large variety of morphology (polyhedral
559 crystals of calcite with well-developed crystal faces and slightly smooth edges and
560 corners, or euhedral rhombic crystals, or prismatic/tooth-like crystals; rosette shapes
561 and short rods of aragonite; prismatic/pillar crystals; calcified fungal hyphae). This
562 confirms that the mineral crystalline morphologies are deeply affected by the different
563 diagenesis stages and are dependent on the nature of the soil environments.
564 Homogeneous micritic calcite crystals are formed during the initial stages of
565 diagenesis underground with a stable environment with wet soil, semi-closed and
566 -redox conditions. In contrast, the presence of polyhedral crystals of calcite with
567 well-developed crystal faces and slightly smooth edges and corners, or euhedral

568 rhombic crystals, or prismatic/tooth-like crystals as well as rosette shapes and short
569 rods of aragonite imply recrystallization through secondary diagenesis with complex
570 and long processes at the soil surface. Aragonite is preferentially formed at higher
571 temperature and with higher concentration of mineral solution in shallow soil
572 environments. The presence of calcified fungal hyphae networks (hair-like, or
573 fungi-form) crystals and pores, cavities and voids somewhere among the micritic
574 mass indicate the role of microorganisms in calcium carbonate crystallization. The
575 extreme environmental conditions and lack of water at the soil surface in hyper-arid
576 deserts hamper microbial life, allowing only highly specialized microbial
577 communities to grow and survive, specifically at the soil surface.

578 The micro-morphological characteristics of the rhizolith cement shows that they
579 can be good proxies for soil formation, evolutions, pedologic and diagenesis processes,
580 especially around and within rhizosphere in desert soil. This study provides a good
581 reference and model for the rhizolith study of deserts worldwide.

582

583 **Declaration of competing interest**

584 The authors declare that they have no known competing financial interests or
585 personal relationships that could have appeared to influence the work reported in this
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587

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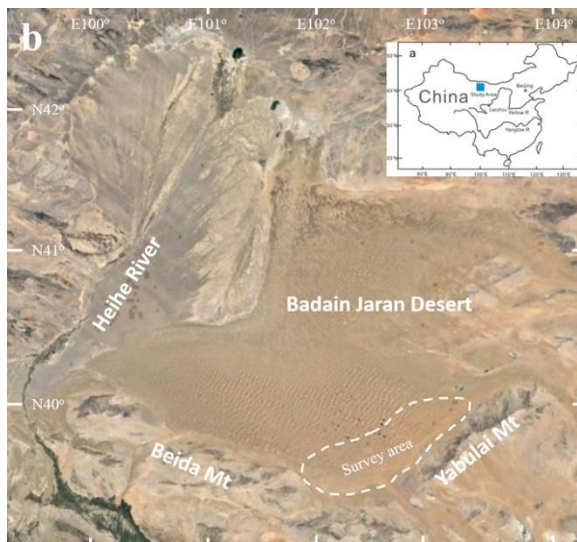
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886 **Figures and Captions**

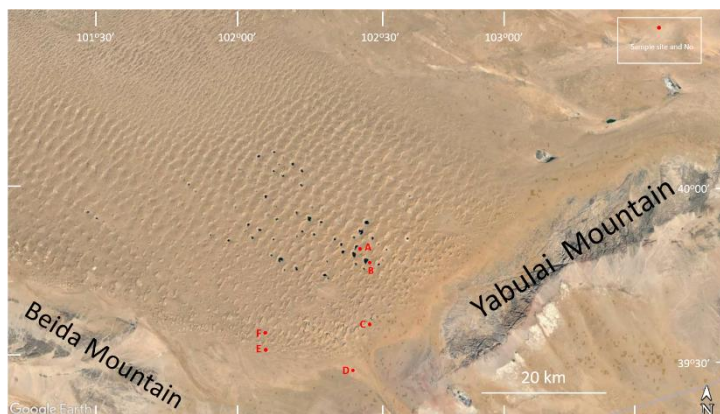
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889 **Fig.1.** Location (blue square) of the BJD in China (a) and the exploration area (white dash lines) in the890 desert (b, Revised from <https://earth.google.com>).

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893 Fig.2. Detail of the sampling sites (A-F) in the southeastern desert. (A-Sumujilin Lake, B-Nuoertu Lake,
 894 C-Baoritaolegai Lake, D-The Gate of National Geological Park of BJD, E & F-random sites among the
 895 dunes. Revised from <https://earth.google.com>)

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898 Fig. 3. a-Fragments of caliche and rhizoliths (The spade length is 100 cm). b-Hard varnished
 899 rhizoliths (The diameter of the coin is 20 mm).

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902 Fig. 4. White pieces of rhizoliths and a root tube. Relicts of fine root hairs within the tube and
 903 weathered rills are observed on the surface of the tube.

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909 **Fig. 5.** a-Vertical PRs dug out of soil (the red screwdriver handle length is 10 cm). b-Root relicts with

910 central cavity and beige peripheral part of PRs in **Fig a.**

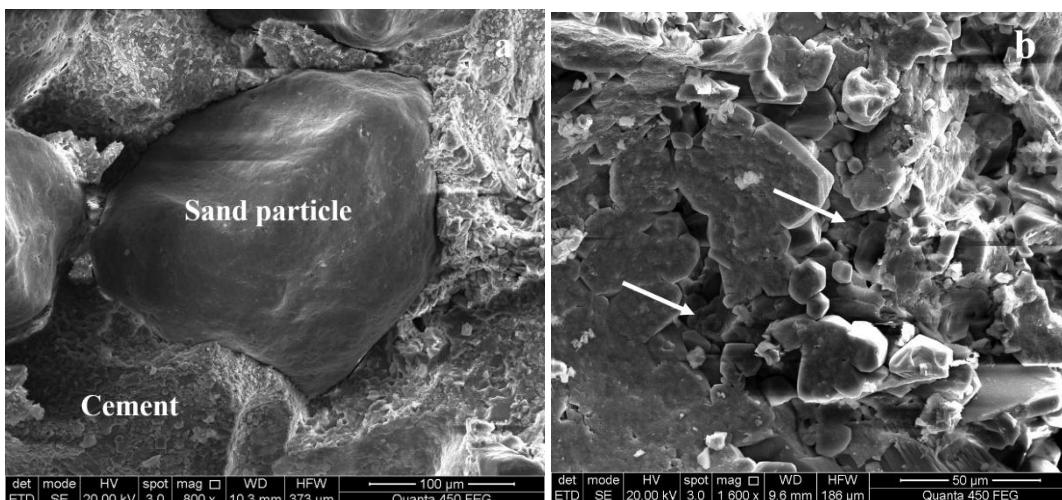
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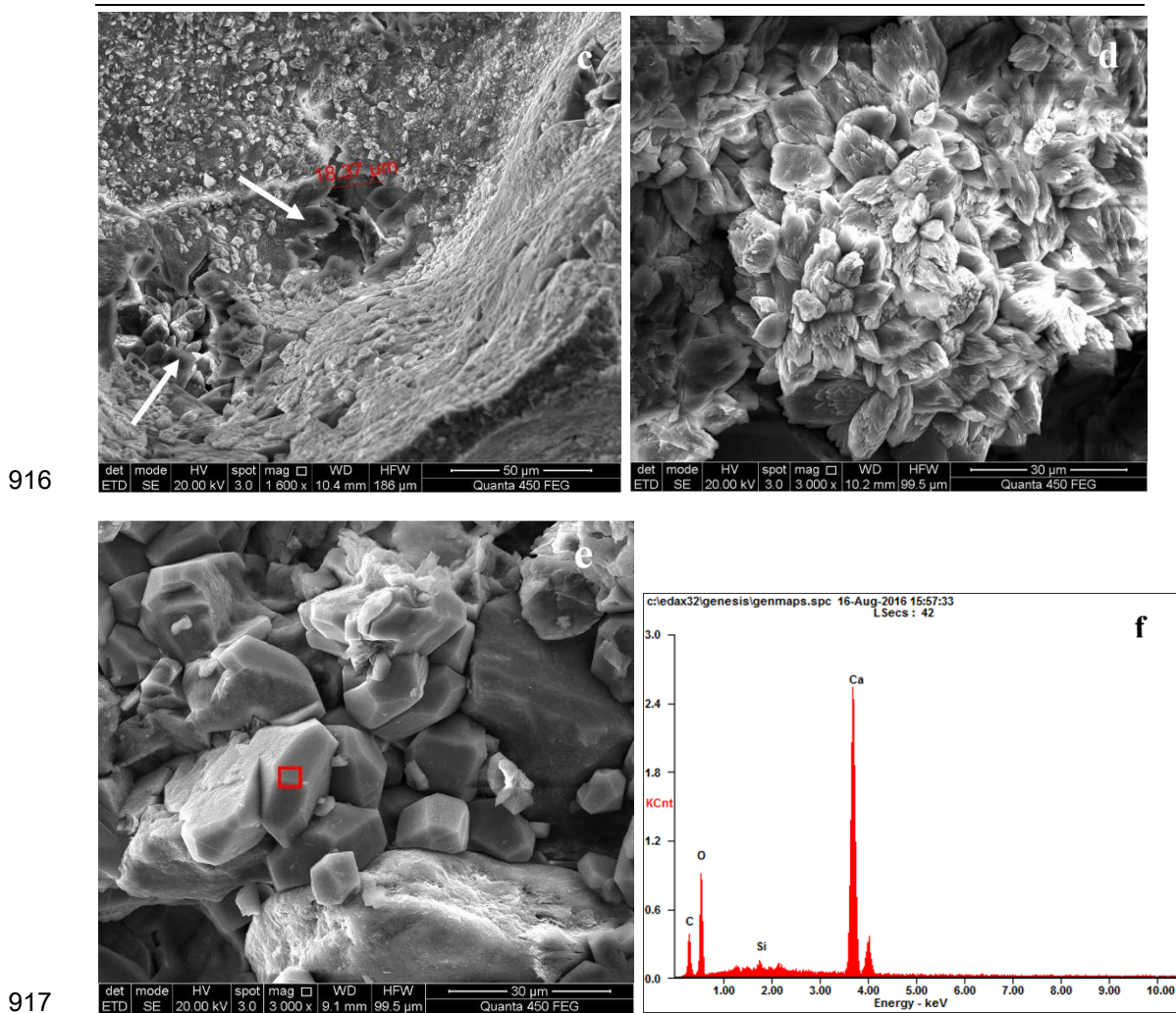
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913 **Fig. 6.** Brown interior of the PR with root relicts.

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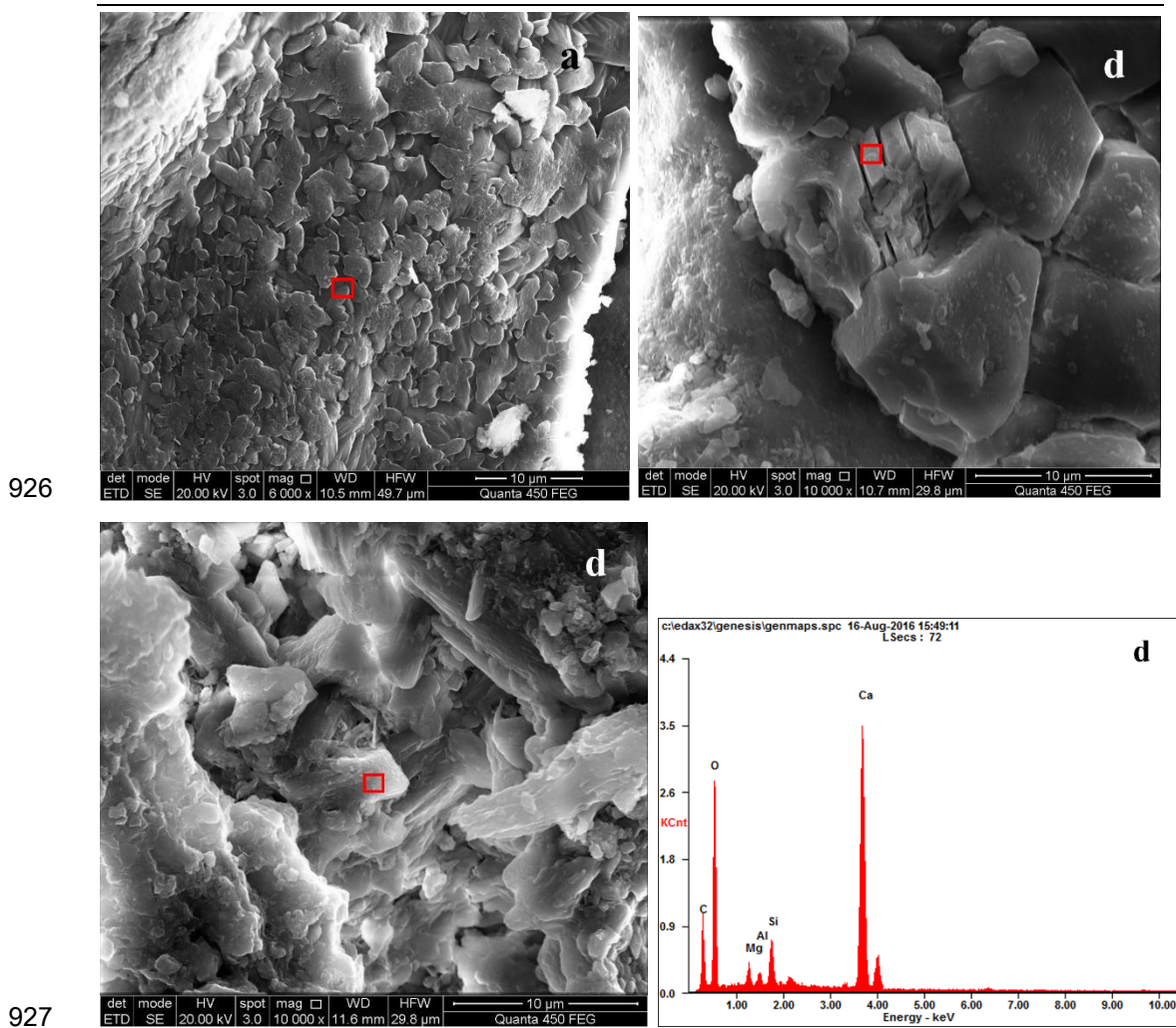
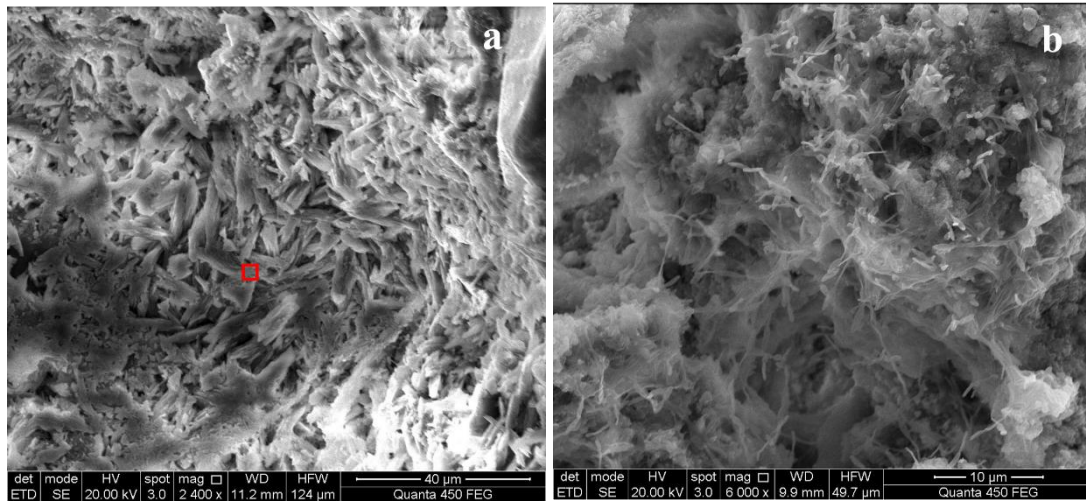
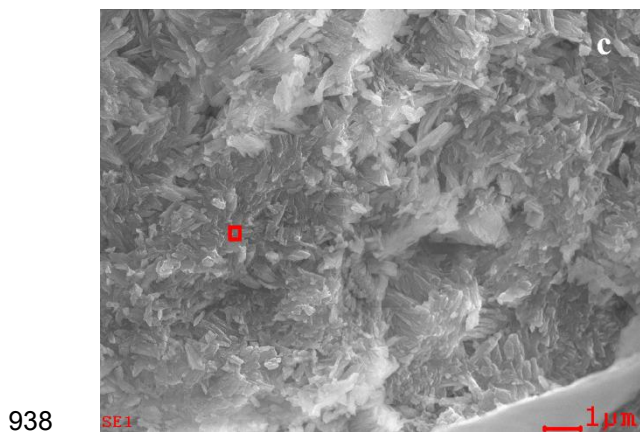
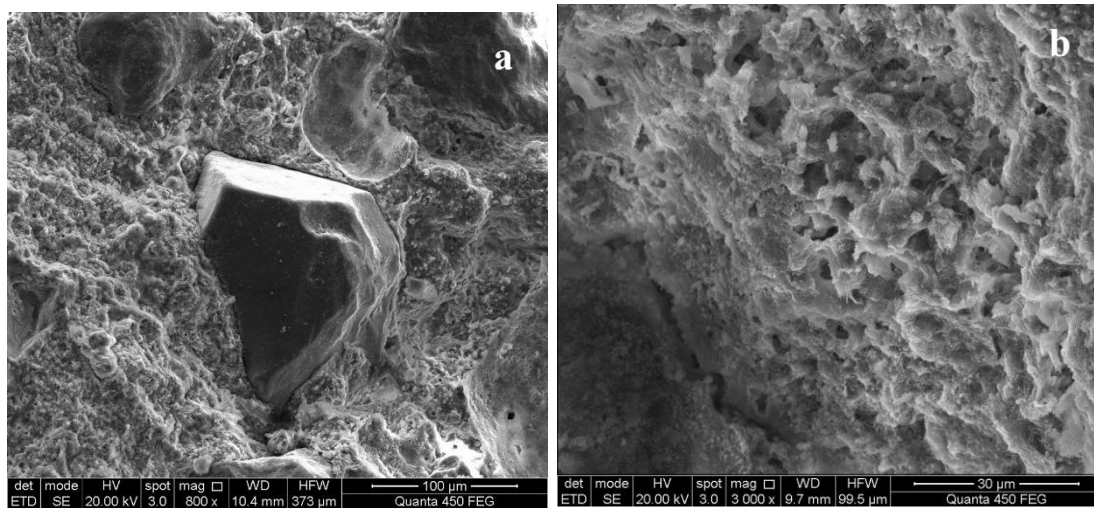


Fig.8. a-Spherular cementing minerals. b-Monocrystalline polyhedral calcites of cement. The EDS results of Fig. a and b were omitted. c-Short rods. d-EDS spectrum (of Fig. c) reveals cement calcium carbonate with a little portion of Mg.

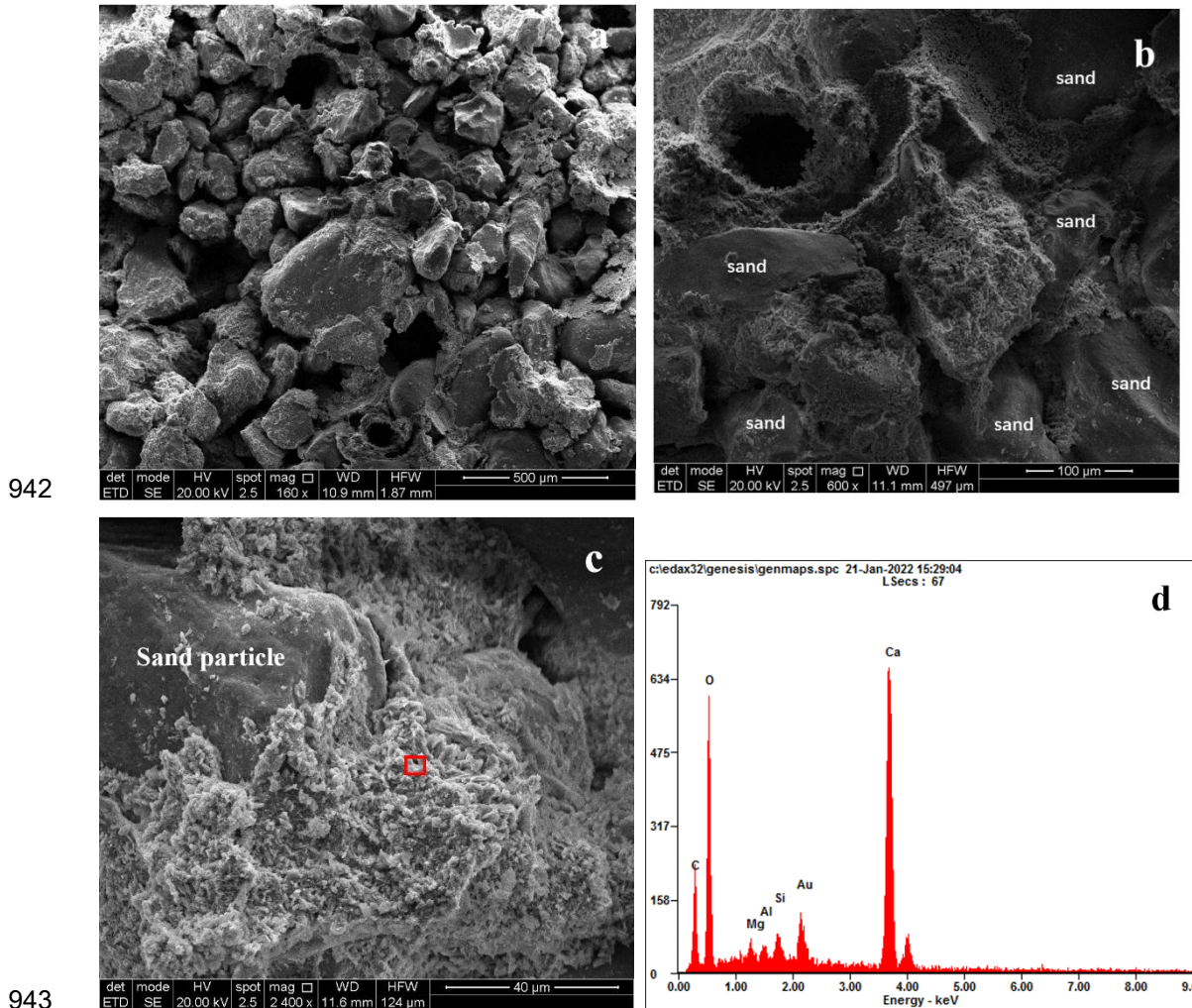


934 **Fig.9.** a-Short rods of aragonite. b-Hair-like, or fungi-form crystals of cement with pores,
 935 and voids.

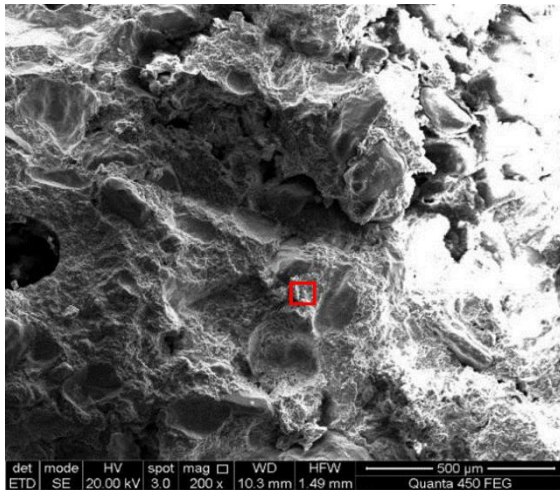
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939 Fig.10. a-Calcite cement around a sand particle, showing homogeneous micritic mass (PR). b-Pores,
 940 cavities and voids among the micritic mass (PR). c-Dense cement of prism/pillar-like calcite (PR).
 941



944 Fig. 11. a-The cementing minerals are mostly as coatings on sand particles and the cement cannot fill
 945 and plug the pores among sand particles. Therefore, large pore spaces among the particles remain
 946 empty and the particles are loose because of a porous cement. b-The cementing minerals are
 947 homogeneous micritic mass. c-The homogeneous micritic mass is forming thin layers on the surfaces
 948 of particles. d-EDS spectrum (of c) reveals that the cement is mainly constituted of calcium carbonate
 949 with only a little Mg.



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951 [Fig. 12.](#) Homogeneous micritic mass.

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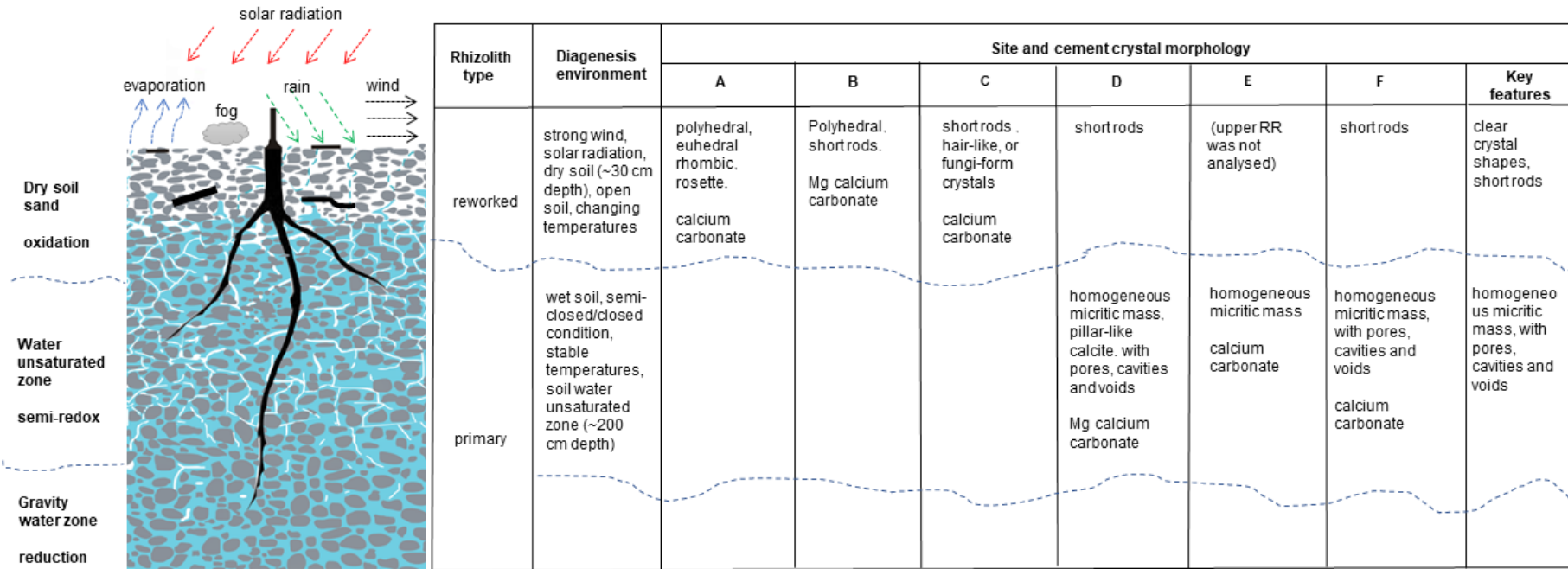
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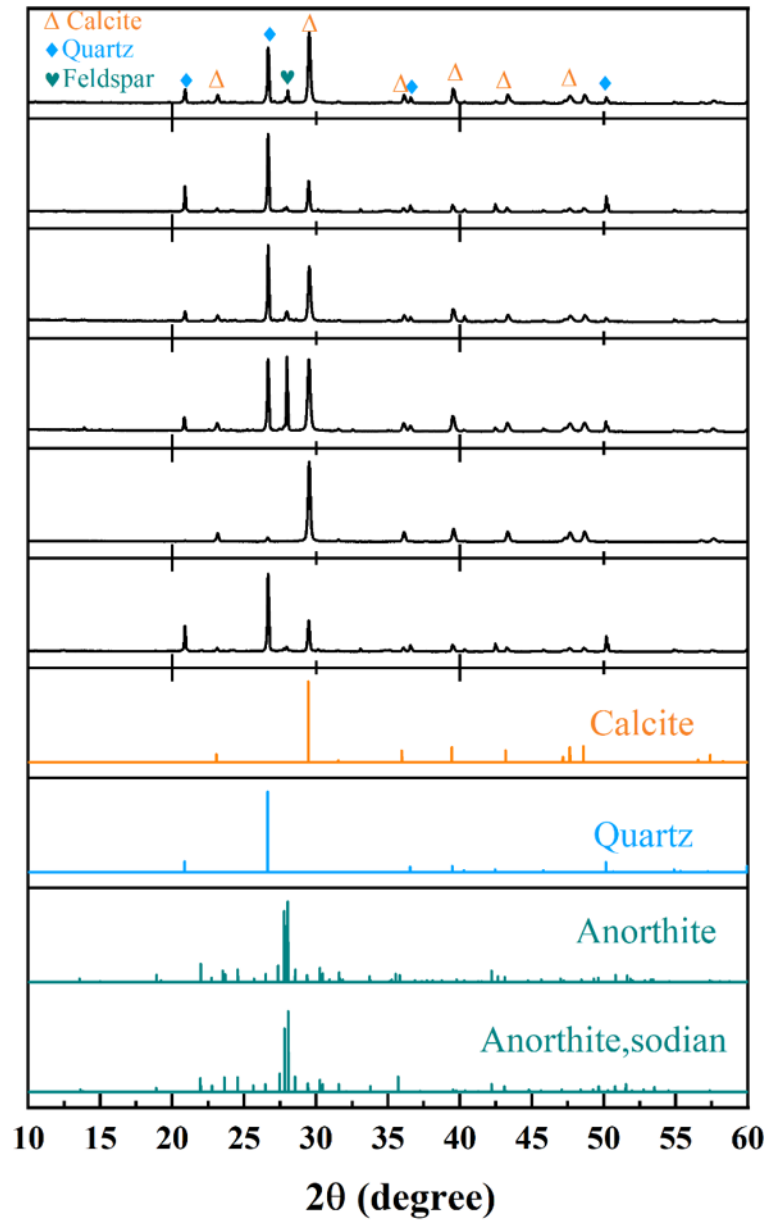
960 Fig. 13. Rhizolith types, diagenesis environment, micro-morphologies and compositions of cementing minerals at different sites.

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966 Fig. 14. XRD patterns of the cements collected at different sites: a-Site A, b-Site B, c-Site C, d-Site D,

967 e-Site E, f-Site F. The standard card numbers of calcite, quartz, and anorthite used here are #86-2334,

968 #85-0797 and #10-0393, respectively.

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